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**Identification and characterization of multiple porcine astrovirus genotypes
in the Hunan province, China**

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25

26 **ABSTRACT**

27 Astroviruses (AstV) can infect a variety of hosts including mammalian and avian species and
28 are commonly associated with enteric infections. Recently mammalian AstVs have been
29 linked to extra-intestinal manifestations, including neurologic disorders in humans, cattle and
30 minks, demonstrating a zoonotic potential. Until now, five porcine AstV (PAstV) genotypes
31 have been identified, with PAstV1, PAstV2, PAstV3 and PAstV5 implicated in cross-species
32 transmission. The knowledge on PAstV epidemiology in China is still limited. In this study,
33 two duplex differential RT-PCRs were developed to investigate the distribution and
34 prevalence of PAstV1, PAstV2, PAstV4 and PAstV5. Two-hundred-eighteen samples were
35 collected from 33 farms and pigs with known diarrhea status in nine regions of the Hunan
36 province in China. Specifically, 126 small intestines, 51 fecal swabs, 20 lungs, 19 spleens and
37 two kidneys were obtained. PAstVs were detected in all nine regions and in 81.8% (27/33) of
38 the investigated pig farms. The overall PAstV prevalence was 46.3% (101/218), with PAstV5
39 as the predominant type with a positive rate of 24.8% (54/218). The prevalence of PAstV4,
40 PAstV1 and PAstV2 was 16.1% (35/218), 14.7% (32/218) and 10.1% (22/218), respectively.
41 Besides being present in intestines and fecal swabs, PAstV RNA was also detected in lungs,
42 spleens and kidneys. Sequencing revealed a high genetic divergence within each genotype
43 and a higher positive rate of PAstV5 was associated with pigs with diarrhea compared to pigs
44 without diarrhea. This study discovered PAstV4 circulating in China for the first time, and
45 revealed PAstV5 as the dominant genotype in pig herds in the Hunan province in China.

46 **Keywords:** Porcine astrovirus; Prevalence; Phylogenetic analysis; China; Pigs.

Introduction

Astroviruses (AstV), which belong to family *Astroviridae*, are small, non-enveloped, positive-sense single-stranded RNA viruses, with genomes of 6.4 to 7.7 kb in length, which are characterized by five- or six-pointed star-like surfaces [3]. Two genera have been defined, namely *Avastrovirus* infecting birds and *Mamastrovirus* infecting mammals [3]. Infection with *Avastrovirus* species often involves intestinal or extra-intestinal manifestations (e.g. damage to the liver, kidney, or the immune system) while infection with *Mamastrovirus* is predominantly associated with gastroenteritis [3]. Recently, member of the *Mamastrovirus* genus have been associated with extra-intestinal manifestations [7, 9, 20, 24, 25], including encephalitis in cattle [16, 26, 27] and a shaking syndrome in mink [1]. These findings may indicate that the clinical significance of AstVs in mammals is increasing.

Porcine astrovirus (PAstV) was first identified by electron microscopy in 1980 [4] and was isolated in 1990 [30]. Since then, PAstVs have been identified worldwide, including Africa, Asia, North America, and South America [10, 14, 33, 35]. Five genetically distinct genotypes (PAstV1 to PAstV5) have been defined with different prevalence and were identified in pig regardless of clinical signs [13, 28, 33]. It has been suggested that PAstV1, PAstV2, PAstV3 and PAstV5 may have crossed host species previously [21, 33]. In China, the knowledge for PAstV is still limited, with only four studies reporting the identification and distribution of PAstV. Specifically, a PAstV sequence belonging to PAstV2 (HQ647383) has been identified in domestic pigs with diarrhea in 2009 [12], a PAstV1 (GQ914773) strain was described in healthy domestic pigs in 2008 [29], and a PAstV2 (KP747573) sequence and a PAstV5 (KP747574) sequence were obtained from healthy domestic piglets [15]. Very

recently, several PAsV2 and PAsV5 sequences were identified in domestic pigs or wild boars in the Sichuan province, China [8]. However, generally, the PAsV genetic diversity and prevalence of different PAsV genotypes in China is still not well understood.

In the present study, we report the discovery of PAsV4 in China and the prevalence of PAsV1, PAsV2, PAsV4 and PAsV5 in domestic pigs from Hunan province, China.

Materials and methods

Sample collection

Two-hundred-and-eighteen independent samples were randomly collected from January to August of 2014 and included 126 small intestines, 51 fecal swabs, 20 lung tissues, 19 spleens and two kidneys. The majority of the samples were from diagnostic case submissions to the College of Veterinary Medicine of Hunan Agricultural University. Samples were included based on availability at the time of sample collection resulting in limited numbers of lung, spleen and kidney samples compared to small intestines and fecal swabs. To avoid possible cross-contaminations, samples were collected with sterile instruments and whenever possible on different days. The samples came from 33 pig farms located in nine regions/cities of the Hunan province, China, including Changsha, Hengyang, Yiyang, Changde, Xiangtan, Chenzhou, Loudi, Zhuzhou and Yueyang. Among the samples, 98 were from pigs with a history of diarrhea, and the remaining 120 samples were from pigs without clinical signs of diarrhea. The age of the pigs sampled ranged from 7 to 60 days. The samples were shipped on ice and kept in a -80 °C freezer until use.

Sample processing and viral RNA extraction

After re-suspending the fecal swabs in 1 ml sterile PBS, they were centrifuged at 4000 rpm for 10 min, and 0.2 ml of the suspension was transferred into a 2 ml Eppendorf tube and used for viral RNA extraction. For tissue samples, approximately 0.1 gram of each the sample was placed into a 2 ml Eppendorf tube containing four 1.5 mm steel balls and were grinding using the Mixer Mill MM 400 (Retsch, Germany) for 1 min. Then 1 ml TRIzol reagent (InvitrogenTM) was added into the 2 ml tubes and RNA was extracted according to the manufacturer's instructions. The viral cDNA was synthesized by using the Transcriptor First Strand cDNA Synthesis Kit (RocheTM) and random primers as described by the manufacturer. The obtained viral cDNA were stored at -80 °C freezer.

Development of two duplex differential RT-PCR assays for detecting PAsTVs

Based on the alignments of the available genome sequences of PAsTV, four pairs of primers were designed within conserved regions aiming to amplify PAsTV1 and PAsTV2 and PAsTV4 and PAsTV5 ([Table 1](#)). As the prevalence of PAsTV3 has been reported to be very low, only one genome of PAsTV3 (JX556691) is available in GenBank, and as the genetic heterogeneity within PAsTV genotypes is large [[33](#)], the prevalence of PAsTV3 was not investigated in the present study. Initially, single-plex RT-PCR assays were designed and tested and once optimized two duplex differential RT-PCRs with the same primer pairs targeting PAsTV1-2 and PAsTV4-5 were developed. The PCR assays were carried out in a 30 µl total reaction volume containing 15 µl PCR mix (TIANGEN, Beijing, China), 0.5 µl of 10 mM of each of the primers, 2 µl cDNA, and nuclease-free H₂O. The amplification reactions were performed under the following conditions: 2 min at 94°C, 35 cycles of 30 s at 94°C, 20 s

at 57°C and 30 s at 72°C, followed by 72 °C for 7 min. The PCR products were then checked on a 0.8 % agarose gel under UV light, and the samples with positive results were recorded.

The sensitivity of the two duplex differential RT-PCR was evaluated by serial dilution of the cDNA used in the single-plex PCR. The specificity of the primers was confirmed by BLAST analysis, and in addition, positive controls for other swine RNA viruses including porcine transmissible gastroenteritis virus (TGEV), porcine reproductive and respiratory syndrome virus (PRRSV), porcine epidemic diarrhea virus (PEDV) and classical swine fever virus (CSFV) were tested with the two duplex differential RT-PCR assays.

DNA sequencing and sequence analysis

Four pairs of primers, located in open reading frame (ORF) 1b or ORF2, were designed to amplify the partial genome sequences of the four PAsV genotypes. The two pairs of primers used for PAsV1 and PAsV2 were the same as the single and duplex differential RT-PCR reactions ([Table 2](#)). The PCR products were checked under UV light, gel purified by QIAquick Gel Extraction Kit (QIAGEN Inc.), and the purified products were sequenced directly using the forward and reverse primers. The obtained sequences were analyzed by DNAMAN 7.0 (Lynnon Corporation) and the phylogenetic analysis was performed by the Neighbor-Joining method with the p-distance model through MEGA 6.0 [\[31\]](#).

Statistical analysis

Differences in prevalence were investigated by chi-square tests using the JMP® Pro12.0.1 software (SAS, Cary, NC, USA). A *P* value less than 0.05 was considered

significant.

GenBank accession numbers

The nucleotide sequences obtained in the present study were deposited in GenBank under the following accession numbers: KY047664 - KY047762

Results

Assay validation

The sensitivity of the duplex differential RT-PCR assays was comparable to the single-plex RT-PCR assays, and the specificity of both duplex-RT-PCR assays and the four single-plex RT-PCR assays was 100% as viral RNA of TGEV, PRRSV, PEDV and CSFV was not detected (data not shown). Examples of the bands obtained with the two duplex differential RT-PCRs separated by agar gel electrophoreses are showed in Fig. 1.

Prevalence of PAsTVs

PAsTV was detected on 27 of the 33 (81.8%) farms investigated, and all of the nine regions in the Hunan province were positive, with an overall PAsTV positive rate of 46.3% (101/218) ([Table 3](#)). All of the four investigated PAsTV genotypes were discovered in the Hunan province, with PAsTV5 having the highest prevalence of 24.8% (54/218), followed by PAsTV4 with a prevalence of 16.1% (35/218). PAsTV1 and PAsTV2 showed low positive rates of 14.7% (32/218) and 10.1% (22/218), respectively.

When the PAsTV prevalence was compared in pigs with or without enteric signs, it was 57.1% (56/98) in pigs with diarrhea compared to 37.5% (45/120) in pigs without diarrhea

which was significantly ($P < 0.05$) different (Table 4). Furthermore, when genotype prevalence rates were compared, PAsTV5 had a significantly ($P < 0.05$) higher infection rate in pigs with enteric signs compared to pigs without diarrhea, while clinical status of a pig did not affect the prevalence of PAsTV1, PAsTV2 and PAsTV4 (Table 4). The sample types with the highest infection rate were small intestines (52.4%) and fecal swabs (49%) (Table 5). PAsTV was also detected in lungs, spleens and kidneys with a considerable high rate (Table 5), which may indicate that PAsTVs could have a wide tissue tropism not limited to the intestine. However, due to the limited sample size for extra-enteric sample types, results need to be interpreted with caution and additional studies to further confirm the obtained results are needed. None of the lung tissues, spleen tissues and kidneys used in this study was obtained from pigs with a history of diarrhea.

Molecular and phylogenetic analysis

Sequencing was successful on 16 PAsTV1 PCR products, 12 PAsTV2 PCR products, 32 PAsTV4 PCR products and 39 PAsTV5 PCR products, and the p-distances between the sequences within the same genotypes were calculated. For PAsTV1, the obtained 16 sequences corresponded to five geographic regions/cities, with the identities between them ranging from 90.4% to 100%. All showed a closer relationship to the GenBank PAsTV1 sequence (KF787112) from the Guianxi province, China, with an average homology of 91.4%. Moreover, in the phylogenetic analysis, the present 16 PAsTV1 sequences clustered into a single clade, and clustered together with PAsTV1 (KF787112) from Guianxi province, China (Fig. 1). Based on the phylogenetic analysis, PAsTV1 could be classified into two subclades,

PAstV1-1 and PAstV1-2, and the sequences obtained in this study clustered all within PAstV1-2. PAstV1-1 includes old PAstV1 sequences identified before 2008 from Japan, Canada and China. Moreover, from the present analysis, PAstV1 showed a close relationship with AstVs recovered from cats, California sea lions, and the classic human AstV (Fig. 2).

For PAstV2, the present 12 sequences corresponded to four different regions and showed identities of 98.2%-100% between each other, with an average of 82.1% identity to other available PAstV2 sequences in GenBank. Phylogenetic analysis indicated that the present PAstV2 sequences from the Hunan province clustered into a monophyletic group (Fig. 3). Interestingly, AstV sequences recovered from porcupines (KJ571486) and roe deer (HM447046) clustered also with the PAstV2 group, possible indicating a recent cross-species transmission.

The 32 PAstV4 sequences were from seven regions of Hunan province with identities of 93.4% -100% between each other. In the phylogenetic analysis, the present sequences were clustered into two subgroups, designated as Hunan-1 and Hunan-2 groups (Fig. 4). The Hunan-1 group showed a close relationship with PAstV4 sequences from Spain, while the Hunan-2 group showed a closer relationship with some Italian PAstV4 strains (Fig. 4). PAstV4 sequences in GenBank have a global distribution and have been identified in Europe, Asia and North America (Fig. 4). Of note, except the PAstV4 sequences identified in the present study, no other PAstV4 sequence have been reported from China to date, although PAstV4 have high prevalence rates in other countries.

PAstV5 was detected in all of the nine investigated regions, with genetic identities of 92.7% to 100% between each other, and an average identity of 97.5% within the genotype.

Moreover, PAsV5 from the Hunan province formed a monophyletic branch in the phylogenetic analysis, and showed a closer relationship to PAsV5 from US pigs than to a PAsV5 sequence (KP747574) previously identified in China (Fig. 5).

Discussion

The present PAsV overall positive rate of 46.3% (101/218) in domestic pigs from the Chinese Hunan province is much higher than the 17.5 % (21/120) reported recently from the Chinese Sichuan province [8], 19.4% (25/129) from South Korea [14], 20.8% (25/120) from Germany [18], and comparable to 34.2%, (67/196) from the Czech Republic [11], while it is lower than the prevalence rate of 79.2% (76/96) from Canada [17], 89% (81/91) from Croatia [6], 67.4%(163/242) from Italy [19], 100% from both Spain (83/83) and Australia (136/136) [35], 85.7% (36/42) from Hungary [35], and 64% (326/509) from the USA [33]. Moreover, in previous studies, PAsV2 or PAsV4 were reported to be the predominant genotypes in domestic pigs [6, 14, 17, 19, 33, 35], while in the present investigation, PAsV5 was firstly revealed to be the predominant genotype (24.8%,54/218) followed by PAsV4 (16.1%, 35/218). This is also different compared to previous investigations in the Sichuan province, China, which indicated prevalence rates of 10% (12/120) for PAsV2 and 7.5% (9/120) for PAsV5 [8]. The different results may be due to differences in the efficacy of different primers used; moreover, PAsV has a large genetic divergence between genotypes but also within each genotype, which makes it is difficult to design universal primers (including degenerate primers) suitable for all know or unknown PAsV strains. On the other hand, the distribution and prevalence of PAsV genotypes may be different among regions or countries.

Under experimental conditions using caesarian-derived, colostrum-deprived 4-day-old pigs, PAsTV1 infection could be associated with mild diarrhea [30]. However, any association of the other four PAsTV genotypes with clinic manifestations in pigs remains undetermined. It has been reported that diarrheic pigs had a higher viral load of PAsTV4 in nursery and growing-finishing groups [35]. In the present study, PAsTVs and more specifically PAsTV5 had a significantly higher prevalence in pigs with diarrhea compared to pigs without diarrhea. This is in contrast to most other studies which reported no significant association of PAsTV infection and diarrhea [5, 17, 19, 28]. Further virus isolation and pathogenicity studies are needed to clarify the importance of this group of viruses in pigs.

Many mammalian AstV have been detected in extra-enteric tissues. Murine AstVs has been detected in the spleen, liver, kidney and mesenteric lymph nodes [22, 34]. Novel bovine and mink AstVs have been discovered in brain tissues [1, 16, 32], and novel human AstVs have been discovered in brain tissues, serum samples, cerebrospinal fluid and urine [24, 25]. PAsTV RNA could be detected in the blood of healthy pigs [5] and in nasal swabs from pigs with acute respiratory symptoms [23]. In the present study, PAsTV has been detected in spleen, lung and kidney tissues. However, due to the limited number of extra-enteric samples available for this study the obtained results require confirmation in additional studies which should include larger numbers of pigs and a defined standard set of samples from each pig. Nevertheless, these data further confirm that mammalian AstV have a wide tissue tropism and are not restricted to enteric tissues. A potential role of PAsTV in extra-enteric diseases including neurologic disorder has been suggested previously [2].

In conclusion, the present study demonstrates the presence of PAsTV1, PAsTV2,

PAstV4 and PAstV5 in domestic pigs located in the Hunan province, China. To our knowledge, this is the first description of PAstV4 in Chinese pigs. Furthermore, the PAstV genotype distribution in China appears to be substantially different compared to other geographic regions with a high prevalence of PAstV5 in domestic pig herds instead of PAstV2 or PAstV4. Within the PAstV genotypes from the Hunan province a high genetic diversity has also been revealed.

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Conflict of interest

The authors declare that they have no conflict of interest.

Compliance with Ethical Standards

The experiments were approved and carried out in accordance with animal ethics guidelines and approved protocols of the Hunan Agricultural University.

References

1. Blomström AL, Widen F, Hammer AS, Belak S, Berg M (2010) Detection of a novel astrovirus in brain tissue of mink suffering from shaking mink syndrome by use of viral metagenomics. *J Clin Microbiol* 48: 4392-4396
2. Blomstrom AL, Ley C, Jacobson M (2014) Astrovirus as a possible cause of

- congenital tremor type AII in piglets? *Acta Vet Scand* 56: 82
3. Bosch A, Guix S, Krishna NK, Méndez E, Monroe SS, Pantin-Jackwood M, Schultz-Cherry S (2011) Family Astroviridae. In: King AMQ, Lefkowitz E, Adams MJ, Carstens EB (eds) *Virus Taxonomy: Classification and Nomenclature of Viruses* (Ninth report of the International Committee on the Taxonomy of Viruses). Elsevier Academic Press, New York, pp 953-959
4. Bridger JC (1980) Detection by electron microscopy of caliciviruses, astroviruses and rotavirus-like particles in the faeces of piglets with diarrhoea. *Vet Rec* 107: 532-533
5. Brnic D, Prpic J, Keros T, Roic B, Staresina V, Jemersic L (2013) Porcine astrovirus viremia and high genetic variability in pigs on large holdings in Croatia. *Infect Genet Evol* 14: 258-264
6. Brnic D, Jemersic L, Keros T, Prpic J (2014) High prevalence and genetic heterogeneity of porcine astroviruses in domestic pigs. *Vet J* 202: 390-392
7. Brown JR, Morfopoulou S, Hubb J, Emmett WA, Ip W, Shah D, Brooks T, Paine SM, Anderson G, Virasami A, Tong CY, Clark DA, Plagnol V, Jacques TS, Qasim W, Hubank M, Breuer J (2015) Astrovirus VA1/HMO-C: an increasingly recognized neurotropic pathogen in immunocompromised patients. *Clin Infect Dis* 60: 881-888
8. Cai Y, Yin W, Zhou Y, Li B, Ai L, Pan M, Guo W (2016) Molecular detection of Porcine astrovirus in Sichuan Province, China. *Virol J* 13: 6
9. Cordey S, Vu DL, Schibler M, L'Huillier AG, Brito F, Docquier M, Posfay-Barbe KM, Petty TJ, Turin L, Zdobnov EM, Kaiser L (2016) Astrovirus MLB2, a New Gastroenteric Virus Associated with Meningitis and Disseminated Infection. *Emerg Infect Dis* 22: 846-853
10. De Benedictis P, Schultz-Cherry S, Burnham A, Cattoli G (2011) Astrovirus infections in humans and animals - Molecular biology, genetic diversity, and interspecies transmissions. *Infect Genet Evol* 11: 1529-1544
11. Dufkova L, Scigalkova I, Moutelikova R, Malenovska H, Prodelalova J (2013) Genetic diversity of porcine sapoviruses, kobuviruses, and astroviruses in asymptomatic pigs: an emerging new sapovirus GIII genotype. *Arch Virol* 158: 549-558
12. Lan D, Ji W, Shan T, Cui L, Yang Z, Yuan C, Hua X (2011) Molecular characterization of a porcine astrovirus strain in China. *Arch Virol* 156: 1869-1875
13. Laurin MA, Dastor M, L'Homme Y (2011) Detection and genetic characterization of a novel pig astrovirus: relationship to other astroviruses. *Arch Virol* 156: 2095-2099
14. Lee MH, Jeoung HY, Park HR, Lim JA, Song JY, An DJ (2013) Phylogenetic analysis of porcine astrovirus in domestic pigs and wild boars in South Korea. *Virus Genes* 46: 175-181
15. Li JS, Li MZ, Zheng LS, Liu N, Li DD, Duan ZJ (2015) Identification and genetic characterization of two porcine astroviruses from domestic piglets in China. *Arch Virol* 160: 3079-3084
16. Li L, Diab S, McGraw S, Barr B, Traslavina R, Higgins R, Talbot T, Blanchard P, Rimoldi G, Fahsbender E, Page B, Phan TG, Wang C, Deng X, Pesavento P, Delwart E (2013) Divergent astrovirus associated with neurologic disease in cattle. *Emerg Infect Dis* 19: 1385-1392

17. Luo Z, Roi S, Dastor M, Gallice E, Laurin MA, L'Homme Y (2011) Multiple novel and prevalent astroviruses in pigs. *Vet Microbiol* 149: 316-323
18. Machnowska P, Ellerbroek L, Johne R (2014) Detection and characterization of potentially zoonotic viruses in faeces of pigs at slaughter in Germany. *Vet Microbiol* 168: 60-68
19. Monini M, Di Bartolo I, Ianiro G, Angeloni G, Magistrali CF, Ostanello F, Ruggeri FM (2015) Detection and molecular characterization of zoonotic viruses in swine fecal samples in Italian pig herds. *Arch Virol* 160: 2547-2556
20. Naccache SN, Peggs KS, Mattes FM, Phadke R, Garson JA, Grant P, Samayoa E, Federman S, Miller S, Lunn MP, Gant V, Chiu CY (2015) Diagnosis of neuroinvasive astrovirus infection in an immunocompromised adult with encephalitis by unbiased next-generation sequencing. *Clin Infect Dis* 60: 919-923
21. Nagai M, Omatsu T, Aoki H, Otomaru K, Uto T, Koizumi M, Minami-Fukuda F, Takai H, Murakami T, Masuda T, Yamasato H, Shiokawa M, Tsuchiaka S, Naoi Y, Sano K, Okazaki S, Katayama Y, Oba M, Furuya T, Shirai J, Mizutani T (2015) Full genome analysis of bovine astrovirus from fecal samples of cattle in Japan: identification of possible interspecies transmission of bovine astrovirus. *Archives of virology* 160: 2491-2501
22. Ng TF, Kondov NO, Hayashimoto N, Uchida R, Cha Y, Beyer AI, Wong W, Pesavento PA, Suemizu H, Muench MO, Delwart E (2013) Identification of an astrovirus commonly infecting laboratory mice in the US and Japan. *PLoS One* 8: e66937
23. Padmanabhan A, Hause BM (2016) Detection and characterization of a novel genotype of porcine astrovirus 4 from nasal swabs from pigs with acute respiratory disease. *Arch Virol* 161: 2575-2579
24. Quan PL, Wagner TA, Briesse T, Torgerson TR, Hornig M, Tashmukhamedova A, Firth C, Palacios G, Baisre-De-Leon A, Paddock CD, Hutchison SK, Egholm M, Zaki SR, Goldman JE, Ochs HD, Lipkin WI (2010) Astrovirus encephalitis in boy with X-linked agammaglobulinemia. *Emerg Infect Dis* 16: 918-925
25. Sato M, Kuroda M, Kasai M, Matsui H, Fukuyama T, Katano H, Tanaka-Taya K (2016) Acute encephalopathy in an immunocompromised boy with astrovirus-MLB1 infection detected by next generation sequencing. *J Clin virol* 78: 66-70
26. Schlottau K, Schulze C, Bilk S, Hanke D, Hoper D, Beer M, Hoffmann B (2016) Detection of a Novel Bovine Astrovirus in a Cow with Encephalitis. *Transbound Emerg Dis* 63: 253-259
27. Seuberlich T, Wuthrich D, Selimovic-Hamza S, Drogemuller C, Oevermann A, Bruggmann R, Bouzalas I (2016) Identification of a second encephalitis-associated astrovirus in cattle. *Emerg Microbes Infect* 5: e5
28. Shan T, Li L, Simmonds P, Wang C, Moeser A, Delwart E (2011) The fecal virome of pigs on a high-density farm. *J Virol* 85: 11697-11708
29. Shan T, Wang C, Tong W, Zheng H, Hua X, Yang S, Guo Y, Zhang W, Tong G (2012) Complete genome of a novel porcine astrovirus. *J Virol* 86: 13820-13821
30. Shimizu M, Shirai J, Narita M, Yamane T (1990) Cytopathic astrovirus isolated from porcine acute gastroenteritis in an established cell line derived from porcine embryonic kidney. *J Clin Microbiol* 28: 201-206

31. Tamura K, Stecher G, Peterson D, Filipski A, Kumar S (2013) MEGA6: Molecular Evolutionary Genetics Analysis version 6.0. *Mol Biol Evol* 30: 2725-2729
32. Wuthrich D, Boujon CL, Truchet L, Selimovic-Hamza S, Oevermann A, Bouzalas IG, Bruggmann R, Seuberlich T (2016) Exploring the virome of cattle with non-suppurative encephalitis of unknown etiology by metagenomics. *Virology* 493: 22-30
33. Xiao CT, Gimenez-Lirola LG, Gerber PF, Jiang YH, Halbur PG, Opriessnig T (2013) Identification and characterization of novel porcine astroviruses (PAstVs) with high prevalence and frequent co-infection of individual pigs with multiple PAstV types. *J Gen Virol* 94: 570-582
34. Yokoyama CC, Loh J, Zhao G, Stappenbeck TS, Wang D, Huang HV, Virgin HW, Thackray LB (2012) Adaptive immunity restricts replication of novel murine astroviruses. *J Virol* 86: 12262-12270
35. Zhou W, Ullman K, Chowdry V, Reining M, Benyeda Z, Baule C, Juremalm M, Wallgren P, Schwarz L, Zhou E, Pedrero SP, Hennig-Pauka I, Segales J, Liu L (2016) Molecular investigations on the prevalence and viral load of enteric viruses in pigs from five European countries. *Vet Microbiol* 182: 75-81

Table 1. Primer information for porcine astrovirus (PAstV) detecting single or duplex RT-PCR assays.

Genotype	Primer	Sequence (5' →3')	Position	Reference sequence	Size
PAstV1	AV1-F	5`-TCCTGTGCTATCAGTTGCTCTC-3`	4032-4053	GQ914773	420
	AV1-R	5`-GATTGCTGGTTTTGGACCTGTG-3`	4430-4451		
PAstV2	AV2-F	5`-AGCAGCTGGATCGTCTTTGGA-3`	3933-3953	JX556690	827
	AV2-R	5`-AGATTCAGCATCCCAGGTTGTT-3`	4738-4759		
PAstV4	AV4-F	5`-TGGCTTCAGGCCTTTGAGTTTT-3`	3588-3609	JX556692	559
	AV4-R	5`-CACCGTCGTAGTAGTCGTGAC-3`	4126-4146		
PAstV5	AV5-F	5`-TGGTACGTRCACAATCTGTTGAA-3`	3562-3584	JX556693	182
	AV5-R	5`-TCAGTGTCTTCCCAACCRTC-3`	3724-3743		

Table 2. Primers used to sequence porcine astroviruses (PAstV).

Genotype	Sequence (5' →3')	Location	Position	Reference sequence	Expected size
PAstV4	F:GTCTATGGRGACGACAGATTGAC	ORF 1b	3660-3682	JX556692	425 bp
	R:TTATGCTTTGGTCCGCCCCTC	ORF 1b	4064-4084		
PAstV5	F:ACCAACTTCCCTCCCGACCC	ORF 1b	3778-3797	JX556693	368 bp
	R:TACGACAAGATCCTATCTGAAAAG	ORF2	4122-4145		

Table 3. Porcine astrovirus (PAstV) genotypes detected in different regions/cities of the Hunan province, China.

Regions	PAstV1	PAstV2	PAstV4	PAstV5	Co-infection	Overall
Changde	1/6 (16.6%)	0/6 (0%)	0/6 (0%)	2/6 (33.3%)	1/6 (16.6%)	2/6 (33.3%)
Changsha	8/85 (9.4%)	12/85 (14.1%)	21/85 (24.7%)	23/85 (27.1%)	18/85(21.2%)	46/85 (54.1%)
Xiangtan	4/22 (18.2%)	0/22 (0%)	4/22 (18.2%)	7/22 (31.8%)	5/22(22.7%)	10/22 (45.5%)
Chenzhou	2/19 (10.5%)	1/19 (5.3%)	2/19 (10.5%)	5/19 (26.3%)	2/19 (10.5%)	8/19 (42.1%)
Hengyang	8/39 (20.5%)	3/39 (7.7%)	4/39 (10.3%)	6/39 (15.4%)	8/39 (20.5%)	13/39 (33.3%)
Loudi	0/4 (0%)	1/4 (25%)	0/4 (0%)	2/4 (50%)	0/4 (0%)	3/4(75%)
Zhuzhou	3/15 (13.3%)	3/15 (20%)	1/15 (6.7%)	2/15 (13.3%)	3/15 (13.3%)	6/16 (40%)
Yiyang	2/16 (12.5%)	2/16 (12.5%)	1/16 (6.3%)	3/16 (18.7%)	4/16 (25%)	4/16 (25%)
Yueyang	4/12 (33.3%)	0/12 (0%)	2/12 (16.7%)	4/12 (33.3%)	1/12(8.3%)	9/12 (75%)
Total	32/218 (14.7%)	22/218 (10.1%)	35/218 (16.1%)	54/218 (24.8%)	42/218(19.3%)	101/218 (46.3%)

Table 4. Porcine astrovirus (PAstV) infection rate by genotype in pigs with a history of diarrhea or without diarrhea.

Disease Status	PAstV1	PAstV2	PAstV4	PAstV5	Overall
No diarrhea	15.8% (19/120)	11.7% (14/120)	14.2% (17/120)	20% (24/120)	37.5% (45/120)
Diarrhea	12.2% (12/98)	8.2% (8/98)	18.4% (18/98)	31.6% (31/98)	57.1% (56/98)

Table 5. Infection rate of different porcine astroviruses (PAstV) genotypes in selected samples

types.

Sample type	PAstV1	PAstV2	PAstV4	PAstV5	Overall
Small intestine	12.7% (16/126)	9.5% (12/126)	15.9% (20/126)	29.4% (37/126)	52.4% (66/126)
Fecal swab	17.6% (9/51)	7.8% (4/51)	25.5% (13/51)	27.5% (14/51)	49% (25/51)
Spleen	5.3% (1/19)	10.5% (2/19)	5.3% (1/19)	15.8% (3/19)	15.8% (3/19)
Lung	20% (4/20)	20% (4/20)	0% (0/20)	5% (1/20)	25% (5/20)
Kidney	50% (1/2)	50% (1/2)	50% (1/2)	0%	100% (2/2)

Figure legends

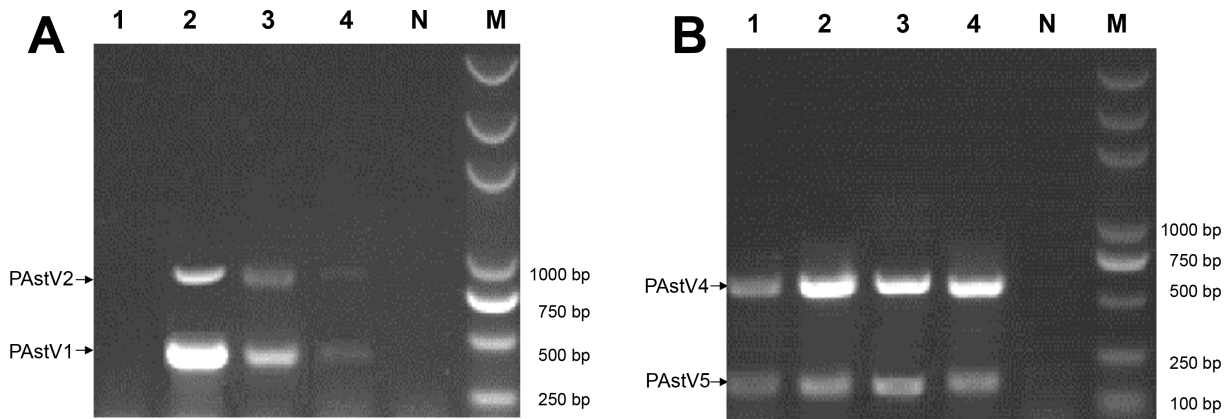


Fig.1 Gel-based electrophoresis of several selected samples to demonstrate the duplex differential RT-PCR outcome. The PCR products were separated on a 0.8 % agarose gel. (A) Duplex differential RT-PCR for PAsV1 (420bp) and PAsV2 (827bp). Lanes 1-4, selected clinic samples, lane 1 (negative), lanes 2-4 (positive for both PAsV1 and PAsV2); N, negative control; M, DNA molecular marker. (B) Duplex differential RT-PCR for PAsV4 (559bp) and PAsV5 (182bp). Lanes 1-4, selected clinical samples, positive for both PAsV4 and PAsV5; N, negative control; M, DNA molecular marker.



Fig. 2 Phylogenetic analysis of PASTV1 based on the 16 sequences identified in the present study and 20 additional PASTV1 sequences obtained through GenBank. The reference sequences of PASTV2 to PASTV5 were included for comparison. The evolutionary tree was inferred using the Neighbor-Joining method with the p-distance model. The percentage of replicate trees in which the associated sequences clustered together in the bootstrap test (1000

replicates) are shown next to the branches (only >60% was shown). The tree is drawn to scale, with branch lengths in the same units as those of the evolutionary distances used to infer the phylogenetic tree. All positions containing gaps and missing data were eliminated. There were a total of 304 positions in the final dataset. The PAstV1 strains identified presently were indicated with black diamonds. The evolutionary analyses were conducted in MEGA6.

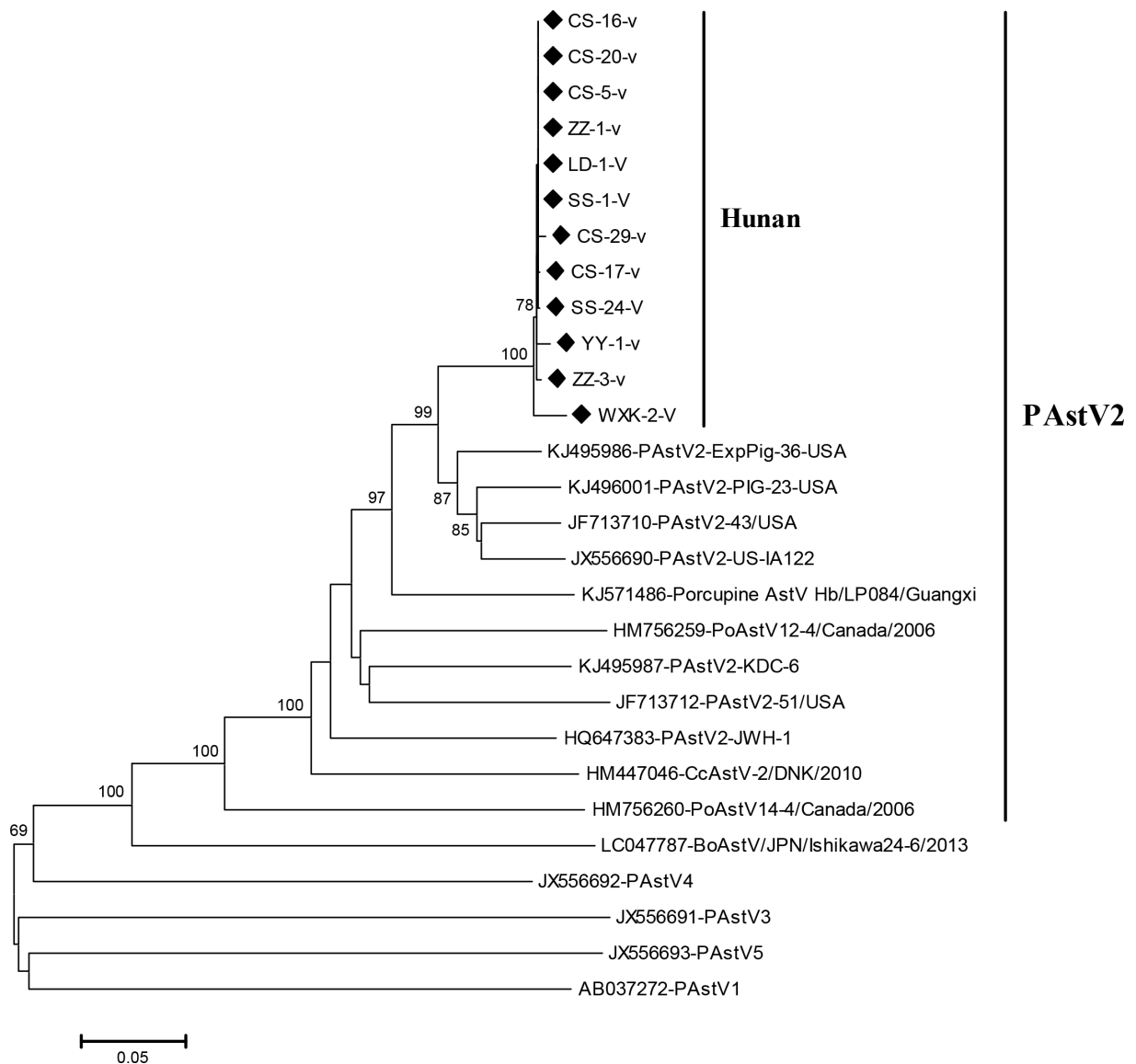


Fig. 3 Phylogenetic analysis of PAstV2 based on the 12 sequences identified in the present study and nine additional PAstV2 sequences obtained through GenBank. The reference sequences of PAstV1, PAstV3, PAstV4, PAstV5 and AstV sequences obtained from porcupine,

429 roe deer, and cattle were included for comparison. The evolutionary tree was inferred using
430 the Neighbor-Joining method with the p-distance model. The percentage of replicate trees in
431 which the associated sequences clustered together in the bootstrap test (1000 replicates) are
432 shown next to the branches (only >60% was shown). The tree is drawn to scale, with branch
433 lengths in the same units as those of the evolutionary distances used to infer the phylogenetic
434 tree. All positions containing gaps and missing data were eliminated. There were a total of
435 748 positions in the final dataset. The PAsV2 strains identified presently are indicated by
436 black diamonds. The evolutionary analyses were conducted in MEGA6.



Fig. 4 Phylogenetic analysis of PstV4 based on the 32 PstV4 sequences obtained in the

439 present study and 61 PAsV4 sequences available through GenBank. The reference sequences
440 of PAsV1, PAsV2, PAsV3 and PAsV5 were included for comparison. The evolutionary tree
441 was inferred using the Neighbor-Joining method with the p-distance model. The percentage of
442 replicate trees in which the associated sequences clustered together in the bootstrap test (1000
443 replicates) are shown next to the branches (only >60% was shown). The tree is drawn to scale,
444 with branch lengths in the same units as those of the evolutionary distances used to infer the
445 phylogenetic tree. All positions containing gaps and missing data were eliminated. There were
446 a total of 189 positions in the final dataset. The PAsV4 strains identified in the present study
447 are indicated by black diamonds. The evolutionary analyses were conducted in MEGA6.

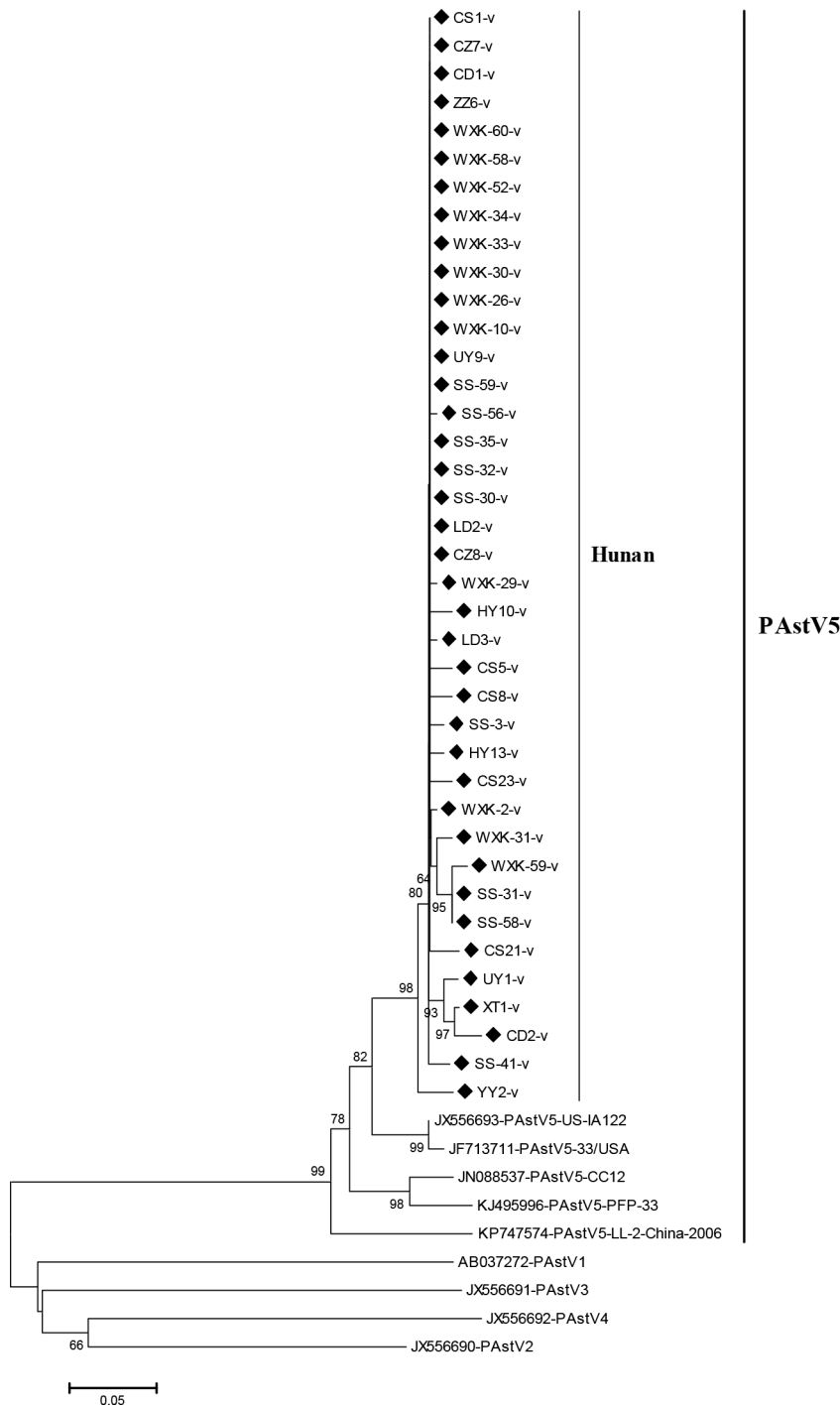


Fig. 5 Phylogenetic analysis of PASTV5 based on the 39 PASTV5 sequences identified in the present study and five PASTV5 sequences available through GenBank. The reference sequences of PASTV1, PASTV2, PASTV3 and PASTV4 were included for comparison. The evolutionary tree was inferred using the Neighbor-Joining method with the p-distance model. The percentage of replicate trees in which the associated sequences clustered together in the

454 bootstrap test (1000 replicates) are shown next to the branches (only >60% was shown). The
455 tree is drawn to scale, with branch lengths in the same units as those of the evolutionary
456 distances used to infer the phylogenetic tree. All positions containing gaps and missing data
457 were eliminated. There were a total of 229 positions in the final dataset. The PAsV5 strains
458 identified in the present study are indicated with black diamonds. The evolutionary analyses
459 were conducted in MEGA6.